SEARCHING FOR PLANETS IN THE HYADES.
I. THE KECK RADIAL VELOCITY SURVEY [1]

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ABSTRACT

We describe a high-precision radial velocity search for jovian-mass companions to main sequence stars in the Hyades star cluster. The Hyades provides an extremely well controlled sample of stars of the same age, the same metallicity, and a common birth and early dynamical environment. This sample allows us to explore the dependence of the process of planet formation on only a single independent variable: the stellar mass. In this paper we describe the survey and summarize results for the first five years.

Subject headings: planetary systems — open clusters and associations: individual (Hyades) — techniques: radial velocities

1. INTRODUCTION

The discoveries of jovian-mass companions around other stars are finally supplying the observational data to test the widely held belief that planet-formation should be a natural result of star-formation (Marcy et al. 2000). The sub-stellar mass companions found so far demonstrate an astonishingly wide diversity of systems. There are jovian mass planets in orbits with semimajor axes as small as 10 stellar radii. Eccentric orbits appear to be the rule rather than the exception. For practical purposes, most surveys so far have targeted relatively nearby dwarf field stars similar to the Sun. These inhomogeneous samples were adequate for discovering the first extra-solar planets. However, as planet search programs now work on the problem of characterization rather than mere discovery of extra-solar planetary systems, the target lists must be much more carefully defined and selected in order to limit the number of free parameters in the sample. Several different types of surveys need to be undertaken, each of which is designed to answer a specific focused scientific question about the physics of planetary system formation.

We are conducting a survey of dwarf stars in the nearby Hyades star cluster to investigate the dependence of planetary system formation on the mass of the parent star. Young open clusters have a number of advantages, as well as disadvantages as samples for extrasolar planet surveys. The target stars form a highly homogeneous sample of stars that is coeval with a well determined age. The stars have uniform initial internal chemical composition, removing issues of stellar metallicity. The birth environment of the cluster is relatively well understood. The major in-

dependent variable in the sample is the mass of the star. While such a study can be conducted with field stars, one must be very careful because field stars are not a homogeneous sample. Their metallicities can span a very wide range, the ages are difficult to determine well, and their birth environments and locations are largely unknown. Disentangling the complex intertwined effects of all of the factors that might influence the properties of any detected planetary systems is significantly more difficult in a volume or magnitude limited sample of solar-neighborhood field stars.

In Section 2 we discuss the suitability of the Hyades as a laboratory for exploring the dependence of planet formation on stellar mass. Section 3 presents the technical aspects of the radial velocity survey using the Keck 1 telescope and its HIRES spectrometer. Preliminary results are presented in Section 4.

2. SEARCHING FOR PLANETS IN A STAR CLUSTER

The distribution of stellar masses in a star cluster is described by the the stellar initial mass function (IMF). While the detailed physics that determines the actual shape of the IMF in a cluster is still not well understood, it has become clear that there are not huge variations in the IMF from one region to another (Meyer et al. 2000). We wish to investigate how, in turn, the mass of the star affects the properties of any planetary system that may form around it. Do massive stars form massive planets, or does tidal truncation (Lin & Papaloizou 1986) limit the size to which a planet can grow? What role does early dynamical evolution play in systems with various mass stars? Do

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low mass stars form fewer planets, or perhaps lower mass planets? The Hyades star cluster is an excellent place to seek answers to these questions.

2.1. *Planet Formation in a Cluster Environment*

Stars in a cluster share a common birth environment, whereas the location and early dynamical environment of field stars is largely unknown, except perhaps for the sun (Adams & Laughlin 2001). The stellar birth environment can significantly influence the formation and early evolution of both planetary and binary star systems. The planet-forming disks can be disrupted by close stellar encounters, and by the UV radiation from nearby hot stars. Newly formed planetary systems are subject to tidal disruption in the dense stellar environment of a young cluster.

Armitage (2000) considered the effects of disk photoevaporation by ultraviolet radiation from massive stars. Giant planet formation can be suppressed if the disk is destroyed on a timescale shorter than the planetary core growth time of several million years. Armitage computed the disk photoevaporation lifetime as a function of the number of stars in the cluster and the position of the star within the cluster, and concluded that this process suppresses giant planet formation in clusters of $\sim 10^5$ stars out to a distance of about 1 parsec, and possibly farther from the cluster center. If we accept the conventional wisdom that the very short-period giant planets (e.g. 51 Peg b) are formed in the disk at several AU and then migrate inward through tidal interactions with the disk (Bodenheimer et al. 2000), then the incidence of such short-period giant planet systems will be lower in richer clusters because the disk must last sufficiently long after planet formation to allow for the inward migration. If, on the other hand, giant planets form by direct hydrodynamic collapse of gravitational instabilities in the disk (Boss 2000, 2001), then disk photoevaporation is unlikely to affect the giant planet formation process significantly.

Even if a planet-forming circumstellar disk is able to survive destruction by UV photoevaporation processes, the system must still survive the effects of close stellar encounters in the crowded cluster environment. Boffin et al. (1998) and Watkins et al. (1998a,b) investigated the effects of star-disk encounters as well as disk-disk encounters (both coplanar and non-coplanar). These SPH code studies indicate that encounters may cause gravitational instabilities which then lead to fragmentation of the disk and to the formation of additional companion objects to the central star. These simulations assume a disk radius of 1000 AU and model periastron encounter distances ranging from 0.5 to 2.0 disk radii. Scally & Clarke (2001) show that in a dense star forming region such as the Orion Nebular Cluster (ONC), the distribution of stellar encounter distances peaks at 1000 AU, and only 10% of the stars suffer an encounter at less than 100 AU in 10^7 years. The observed disk sizes in ONC tend to be significantly smaller than 1000 AU (McCaughrean & O'Dell 1996) and thus Scally & Clarke conclude that protoplanetary disks in ONC are unlikely to be destroyed by close stellar encounters. These results are supported by computations by Bonnell et al. (2001) and by Smith & Bonnell (2001), who find that stellar encounters do not significantly affect planet formation in open clusters.

Even if a open cluster environment will not easily inhibit the formation of giant planets, is it possible for stellar encounters to affect the planetary system dynamical properties? de la Fuente Marcos & de la Fuente Marcos (1997) proposed stellar encounters in open clusters as a means of forming eccentric giant planets such as 16 Cygni Bb (Cochran et al. 1997). They found that a small fraction of the giant planets formed in open clusters could develop large eccentricities, but most systems will be unaffected. Laughlin & Adams (1998) found that while it is possible for scattering by gravitational interactions with binary stars in the birth cluster to account for some number of systems such as 16 Cygni Bb and even for some close-in giant planets such as 51 Peg b, the overall efficiency of the process is too small to account for the observed semi-major axis – eccentricity distribution.

The stellar environment in a globular cluster, however, is significantly different than in an open cluster. Gilliland et al. (2000) used HST WF/PC2 and STIS to search for photometric transits of short period planets in 47 Tucanae. If main sequence stars in 47 Tuc have the same fraction of 51 Peg-like systems as in the solar neighborhood, then this HST program should have found about 15-20 transiting systems among the 34,000 stars monitored for 8 consecutive days. Instead they found none, indicating that the formation rate of these systems is significantly lower in this globular cluster. Davies & Sigurdsson (2001) computed that during the evolution of 47 Tuc, wide planetary systems ($a \gtrsim 0.3$ AU) would probably be disrupted but tighter systems would probably survive, especially in the less dense outer regions of the cluster.

2.2. *The Hyades as a Laboratory for Studying Planet Formation*

The Hyades are the closest and one of the most intensely studied open clusters. The space motion of the Hyades has been extremely well determined (Perryman et al. 1998; de Bruijne et al. 2001) so cluster membership can be determined with high confidence. The cluster currently comprises over 300 probable members, and a total mass of 300-400 $M_\odot$ (Perryman et al. 1998). A large number of spectroscopic metallicity determinations of individual Hyades stars (Chaffee et al. 1971; Branch et al. 1980; Cayrel et al. 1985; Boesgaard & Budge 1988; Boesgaard 1989; Boesgaard & Friel 1990) were combined by Perryman et al. to give a mean metallicity of the Hyades of [Fe/H] = $+0.14 \pm 0.05$. Much of the scatter in these [Fe/H] values is likely due to differences in the analysis techniques rather than real star-to-star abundance variations. Smith & Ruck (1997) find a mean [Fe/H] = $+0.13$ from analysis of strong Ca II 8542Å and Mg I 8806Å lines. Cayrel et al. (1985) found that [Fe/H] = $+0.12 \pm 0.03$ for 10 Hyades dwarfs, but that 2 other Hyades stars (HD 27859 = vB 52 and HD 27685 = vB 39) had anomalously low [Fe/H] of $+0.028$ which they attributed to the high level of chromospheric activity in these stars. Perryman et al. (1998) fit a theoretical ZAMS to the Hyades, and derive a helium content $Y = 0.26 \pm 0.02$, which agrees closely with the value obtained by Lebreton et al. (2001) of $Y = 0.255 \pm 0.013$ as well as with the solar value of $Y = 0.2659$. Isochrone fitting to the Hyades main sequence turn off then gives a cluster ago of 625 ± 50 My, in excellent agreement with pre-

vious determinations of 655 My (Cayrel de Strobel 1990) and 600 My (Torres et al. 1997). de Bruijne et al. (2001) used the Hipparcos proper motions to derive secular parallaxes for Hyades members which they claimed were significantly better than the Hipparcos trigonometric parallaxes. While this analysis does indeed narrow the width of the Hyades main sequence, it does not really alter the theoretical fit to the main sequence or the derived values of Y and Z. However, the very narrow width of the main sequence does support the lack of significant star-to-star metallicity variations among Hyades dwarfs.

While the Hyades are a nearby, homogeneous sample of stars, are they really suitable targets for high-precision radial velocity work? Achieving high velocity precision requires SNR of about 300 in a relatively short exposure on stars that are slowly rotating and are relatively inactive. Hyades dwarfs range in magnitude from about $V = 7.5$ for a late F star through $V = 9 - 11$ for K stars. The M dwarfs range down through significantly fainter magnitudes. The necessary SNR can be achieved on these stars in exposures of 15 minutes or less with the Keck HIRES spectrograph (Vogt et al. 1994). The Hyades dwarfs, at their age of 625 My, have slowed their rotation rates significantly from the rotation rates found in younger clusters such as the Pleiades (Terndrup et al. 2000). Hyades dwarfs show a good correlation between rotation rates and activity (Stauffer et al. 1997; Terndrup et al. 2000). We have selected stars of low $v \sin i$ for our Hyades sample. The major question that we face in the use of Hyades dwarfs for precise radial velocity studies is whether the level of stellar activity in theses stars will be low enough that we will still be able to detect RV variations due to orbital reflex motion on top of the level of intrinsic RV jitter in these stars. Saar & Donahue (1997), Saar et al. (1998), and Santos et al. (2000) have derived empirical relationships between the observed radial velocity "jitter" of single stars presumed not to have planetary mass companions and observable stellar properties such as $v \sin i$ and R'_{HK}. The applicability of such relationships to our Hyades data set is the major subject of Paper II in this series (Paulson et al. 2002).

3. THE KECK RADIAL VELOCITY SURVEY OF HYADES DWARFS

Since 1996 we have been using the Keck 1 telecope with its HIRES (Vogt et al. 1994) spectrograph to conduct high precision radial velocity observations of a sample of 98 Hyades dwarf stars. An I_2 gas absorption cell provides the velocity metric (Libbrecht 1988; Butler et al. 1996). The HIRES spectrograph is set to include the stellar Ca II H & K lines (3933.66, 3968.47Å). These lines fall in a wavelength region free of I_2 gas cell absorption, and thus provide a direct and simultaneous measurement of stellar chromospheric activity for every radial velocity observation. This automatic ability to monitor stellar activity has turned out to be extremely important for the relatively young, chromospherically active Hyades dwarfs. The red limit of the spectrograph setting is 6188Å, near the effective red limit of useful I_2 gas absorption.

The HIRES "B2" entrance aperture ($0.574'' \times 7.0''$ projected on the sky) gives a nominal resolving power of 60,000 and an actual measured resolving power ranging

up to 67,000 depending on position on the CCD. The image derotator is used to keep the slit vertical on the sky. This keeps atmospheric dispersion perpendicular to the spectrograph echelle dispersion, and presents a constant orientation of the telescope pupil to the spectrograph. The Keck HIRES exposure meter, installed in 2000, is used to terminate exposures when the desired SNR is reached, and to give an accurate determination of the photon-weighted mid-exposure time. We did not apply the empirical correction for problems in the HIRES CCD readout electronics derived by Vogt et al. (2000).

The target stars were selected in 1996, before the Hipparcos data for the Hyades stars were released. After the analysis by Perryman et al. (1998) our target list was significantly modified. Several non-members were dropped, and a few new stars were added. The observing list now comprises 98 Hyades dwarfs: 10 F stars, 24 G stars, 44 K stars and 20 M stars. Since the object of this program is to explore the dependence of planet formation on stellar mass, we have taken great care to include a representative sample of lower mass stars. Due to the steepness of the stellar mass-luminosity relation, the overwhelming majority of the telescope time is spent observing these late K and M dwarfs. The stars have been selected to meet the following criteria: 1) classified as a Hyades member by Perryman et al. (1998), 2) commonly accepted by other studies as a Hyades member based on radial velocity, parallax, and proper motion, 3) not in a spectroscopic binary system with orbital period less than ~ 100 years, and 4) stellar rotational velocity $v \sin i \leq 15 \, \text{km s}^{-1}$. The motivation for criteria 1 and 2 is obvious; this is what guarantees the homogeneity of our sample. The prohibition on spectroscopic binary stars is a common feature of virtually all RV planet detection programs. It simply guarantees that there will not be a stellar companion in an orbit small enough to prevent the presence of planetary companions. The limit to small $v \sin i$ is also a common feature of high precision RV programs, and is predicated on practical considerations. Narrow stellar lines are necessary to achieve the very high radial velocity precision required to detect planetary companions. This is the one selection criterion which might introduce some small biases in our stellar sample. Low rotational velocities will probably select for stars with lower levels of stellar activity (Stauffer et al. 1997). In addition, if the stellar rotation rate at the 625 My age of the Hyades is related to the degree of rotational braking of the star by magnetic coupling to a remnant circumstellar disk at earlier times, we may be selecting for stars that had more massive disks, or stars for which the disks survived longer. However, in practice, our $v \sin i$ criterion was actually more of a spectral class criterion. We rejected eight F5 stars, three F6 stars, and one G5 star based solely on $v \sin i$. Of the ten F stars remaining in the survey, we have one F5 star, eight F8 stars, and one F9 star. Thus, a possible bias toward low $\sin i$ is probably applicable only to the sole surviving F5 star HD 29419 (vB 105). We will live with this possible selection effect and bear it in mind when interpreting the results of our survey.

A color-magnitude diagram of our program stars for which parallaxes are available is given in Figure 1. The absolute magnitudes for the stars are computed using the secular parallaxes of de Bruijne et al. (2001) where ever

possible. For those stars too faint to have been included in the Hipparcos catalog, absolute magnitudes from van Altena (1966) were used.

4. PRELIMINARY RESULTS

This observing program has received an average of five to six nights per year on the Keck 1 telescope, starting in the fall of 1996. Since these target stars are on the average about three magnitudes fainter than the targets for most other high precision radial velocity surveys, our Hyades survey has been hard-pressed to get good temporal coverage of all of the target stars. We have tried to obtain at least two good quality velocity measurements of each star per year. The sampling obtained by our scheduling on Keck has been very good for sampling long periods, but extremely poor for sampling possible short periods variations.

We have attempted to assess the velocity precision we have achieved with Keck/HIRES. Figure 2 gives histograms of the variance of the velocity measurements about the mean for our program stars, after any linear trend has been removed. These observed variances will be a combination of measurement uncertainty, intrinsic stellar variability, and possible orbital motion. The median observed rms for the entire sample of Hyades dwarfs is $9.3\,\mathrm{m\,s^{-1}}$. The lower panels of Figure 2 give the distribution of observed variances for the different spectral classes in the sample. We see that in general the observed variance is larger for the F and G stars than it is for the K and M stars. The variances for the stars at the low end of each distribution is undoubtedly dominated by the uncertainty in the measurement process, while the higher variances are probably real. Our velocity measurement procedure gives us an independent assessment of the internal velocity precision which is most likely to be dominated by intrinsic measurement uncertainties. In measuring the velocities for each observation, we divide the spectrum into several hundred small intervals, and perform the spectral modeling for each spectral interval independently. The variance of the velocities computed for each spectral interval is then used to compute an error bar for the mean velocity of each observation. While we normally refer to this as an "internal" error, it is possible that some portion could be intrinsic to the star. For example, if there are velocity fields within the stellar photosphere, then weak photospheric lines could easily have a very different velocity behavior than strong lines. This velocity difference would also vary with any stellar activity cycle. Nevertheless, the mean "internal" error for the F stars is $6.8\,\mathrm{m\,s^{-1}}$, $4.7\,\mathrm{m\,s^{-1}}$ for the G stars, $4.3\,\mathrm{m\,s^{-1}}$ for the K stars, and $5.2\,\mathrm{m\,s^{-1}}$ for the M stars. The observed trend in internal errors with spectral type is the result of the interplay of two different factors: photon statistics, and the intrinsic velocity content of the spectrum. Since our Hyades stars are all at roughly the same distance, the apparent magnitude of a star is a simple monotonic function of the spectral type. Since we have imposed a maximum exposure time of 15 minutes on all of our observations in order to minimize uncertainties in the barycentric correction, observations of the later spectral type stars have lower SNR than the earlier spectral types. Thus, we expect photon statistics to become increasingly important for later spec-

tral types. The competing effect is simply that the stellar spectrum becomes more complex with decreasing stellar effective temperature. The intrinsic velocity information content of a stellar spectrum depends on the mean absolute value of the slope of the spectrum (Butler et al. 1996). This increases significantly for the later spectral types (Bouchy et al. 2001). Thus, we are in the fortunate position of having roughly constant internal measurement errors of 4-6 m s^{-1} for all of our Hyades sample, independent of stellar mass. Paper II discusses the relationship between our measured radial velocity variations of Hyades dwarfs, and stellar chromospheric activity. The fundamental conclusion is that we are able to achieve sufficient velocity precision in our sample of Hyades dwarfs, in spite of their relatively young age, to detect jovian mass planetary companions in orbit around them. Long timescale stellar activity variations, while present and significant, does not prevent us from achieving the fundamental goals of our observing program.

Figure 3 shows examples of the velocity measurements we have obtained. The upper two panels show two stars, HD 285876 (HIP 21138, vB 191) and BD+19 650 (HIP 18946) which show velocities over four years which are constant to $3\,\mathrm{m\,s^{-1}}$. The middle two panels show two stars, BD+08 642 (HIP 19441) and BD+04 810 (HIP 23312) with secular trends in the data, but with an rms about that trend of 3-4 m s^{-1}. The lower two panels show two stars with large scatter in their observed velocities. HD 285625 (HIP 19834) shows a velocity rms of $53\,\mathrm{m\,s^{-1}}$ and HD 286363 (HIP 18322) shows a velocity rms of $16\,\mathrm{m\,s^{-1}}$. Both of these last stars are candidates for having short period planetary companions. Definitive detection of short period velocity variability has proven to be extremely difficult with the scheduling of this program on Keck. Each star is typically observed only twice per year, leading to significant period aliasing and ambiguity for short period RV variations. To alleviate this problem, we are performing follow-up observations of stars showing significant RV scatter using the high resolution spectrograph (HRS) of the Hobby·Eberly Telescope (HET). The queue scheduled nature of the HET will allow us to optimally sample a range of possible short periods. At the conclusion of this Hyades survey, we will place upper limits on companion $m \sin i$ as a function of orbital period for each of our survey targets and we will then compare the frequency of planetary companions to Hyades stars with similar results for field stars.

5. CONCLUSIONS

Star clusters, such as the Hyades, provide an excellent laboratory for investigating the physics of planetary system formation. Most radial velocity surveys for extrasolar planets have used samples of stars with widely ranging and often unknown ages, metallicities, birth environments, and evolutionary histories. However, in the Hyades we have a very well controlled and understood sample of stars in which the primary independent variable is the stellar mass. The goal of this program is to attempt to understand the dependence of the properties of planetary systems on the mass of the central star. With the Hyades we have demonstrated 3–6 m s^{-1} radial velocity precision for main sequence stars between F8 and M2, using the

Keck 1 telescope and its HIRES spectrograph with an I_2 cell as the velocity metric. While these stars are indeed chromospherically active, the activity is not large enough to seriously interfere with our ability to detect jovian-mass companions. A number of promising candidate planetary systems have been identified which will be followed using the Hobby·Eberly Telescope.

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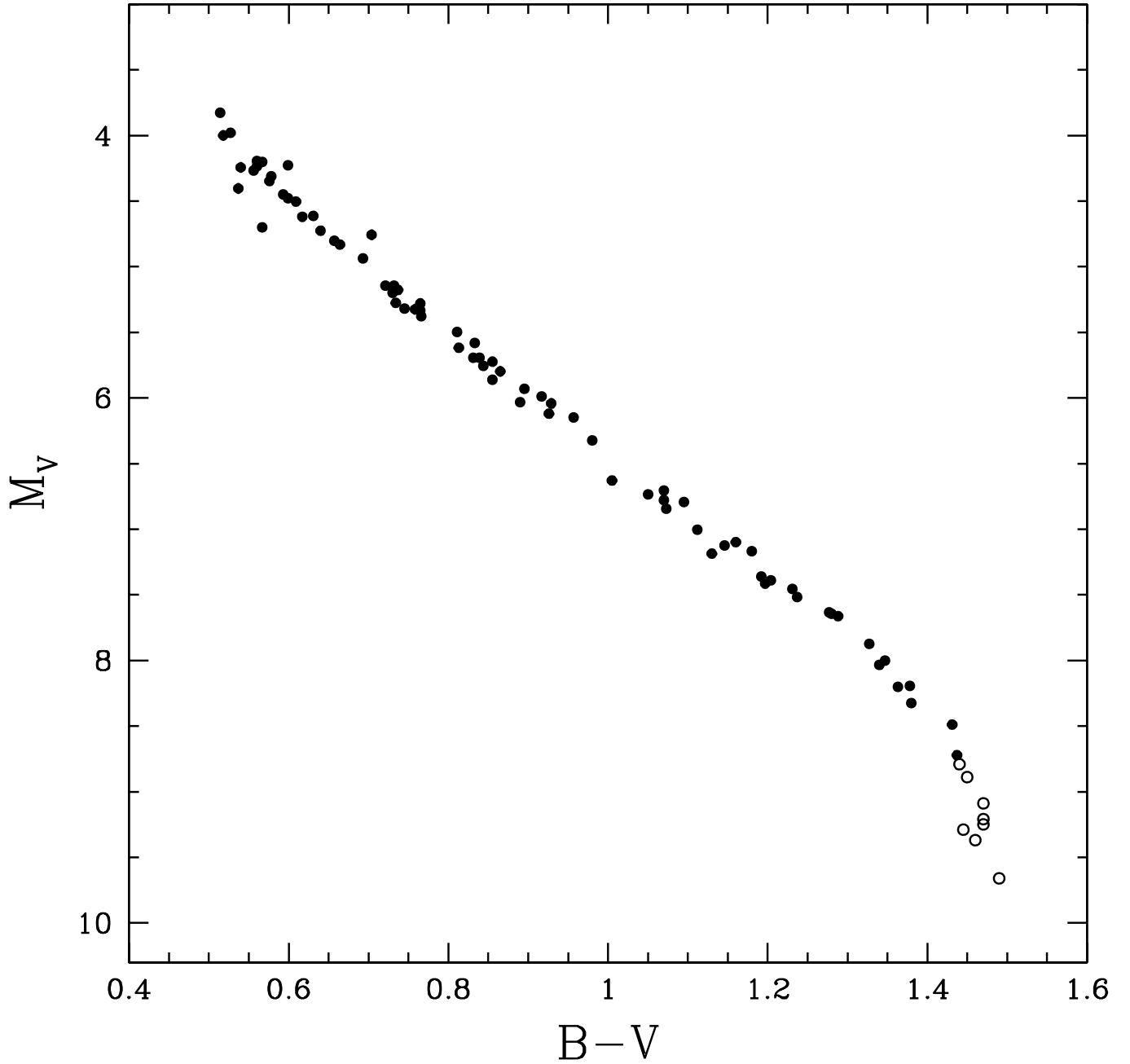—. 1998b, MNRAS, 300, 1214

Fig. 1.— Color-Magnitude diagram for Hyades program stars. The solid circles are program stars in the Hipparcos catalog. The absolute magnitudes for these stars have been computed using the statistical parallaxes from de Bruijne *et al.* (2001). The open circles are stars too faint to be included in the Hipparcos survey. For these stars, absolute magnitudes from van Altena (1966) were used.
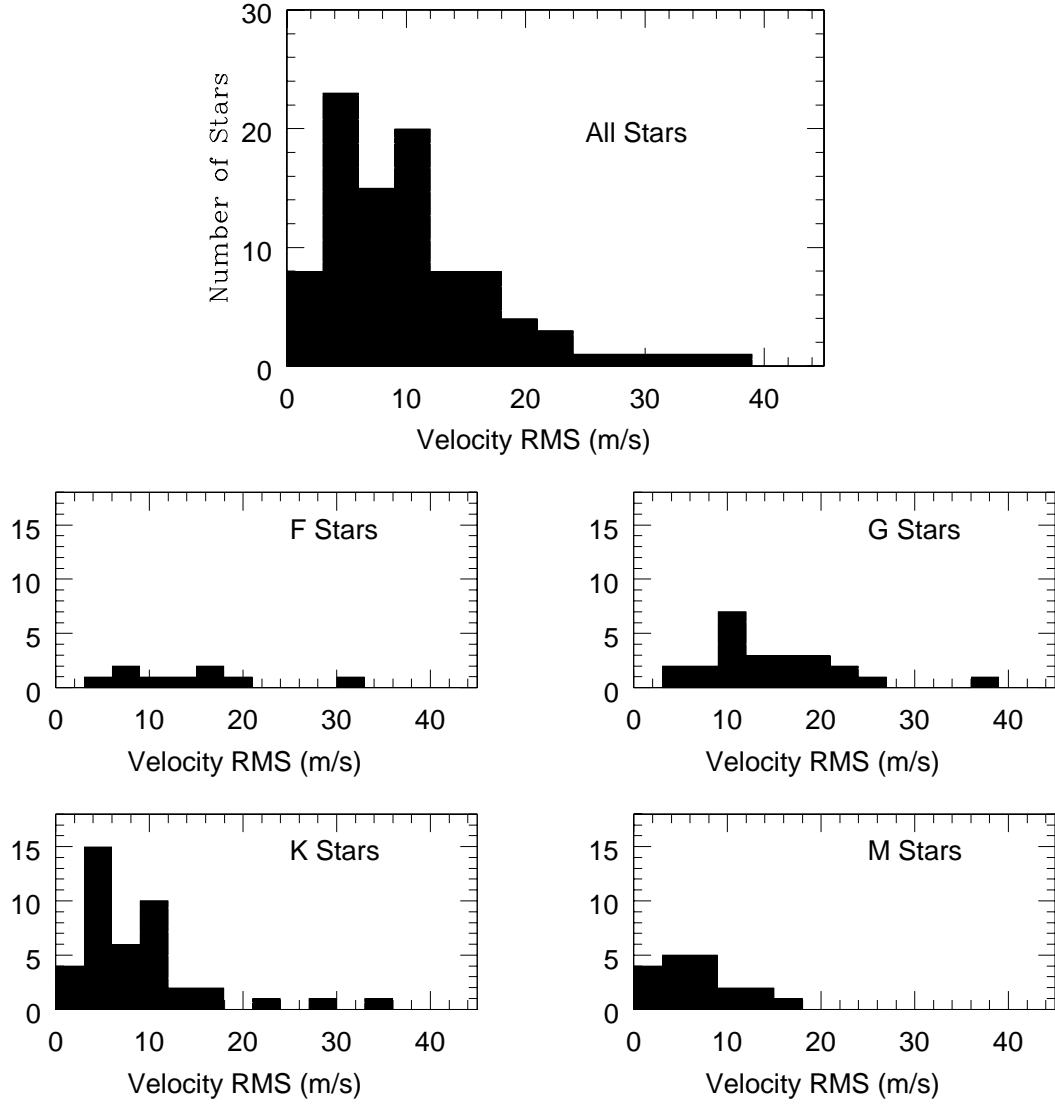
FIG. 2.— The distribution of variances of the velocity measurements of program stars about the mean, after removal of any long-term trends. The upper panel gives results for all stars in the program, and the lower panels break out the results by stellar spectral class. The histograms do not include four stars (1 F star, 2 K stars, and 1 M star) with velocity RMS greater than $40\,\mathrm{m\,s^{-1}}$.
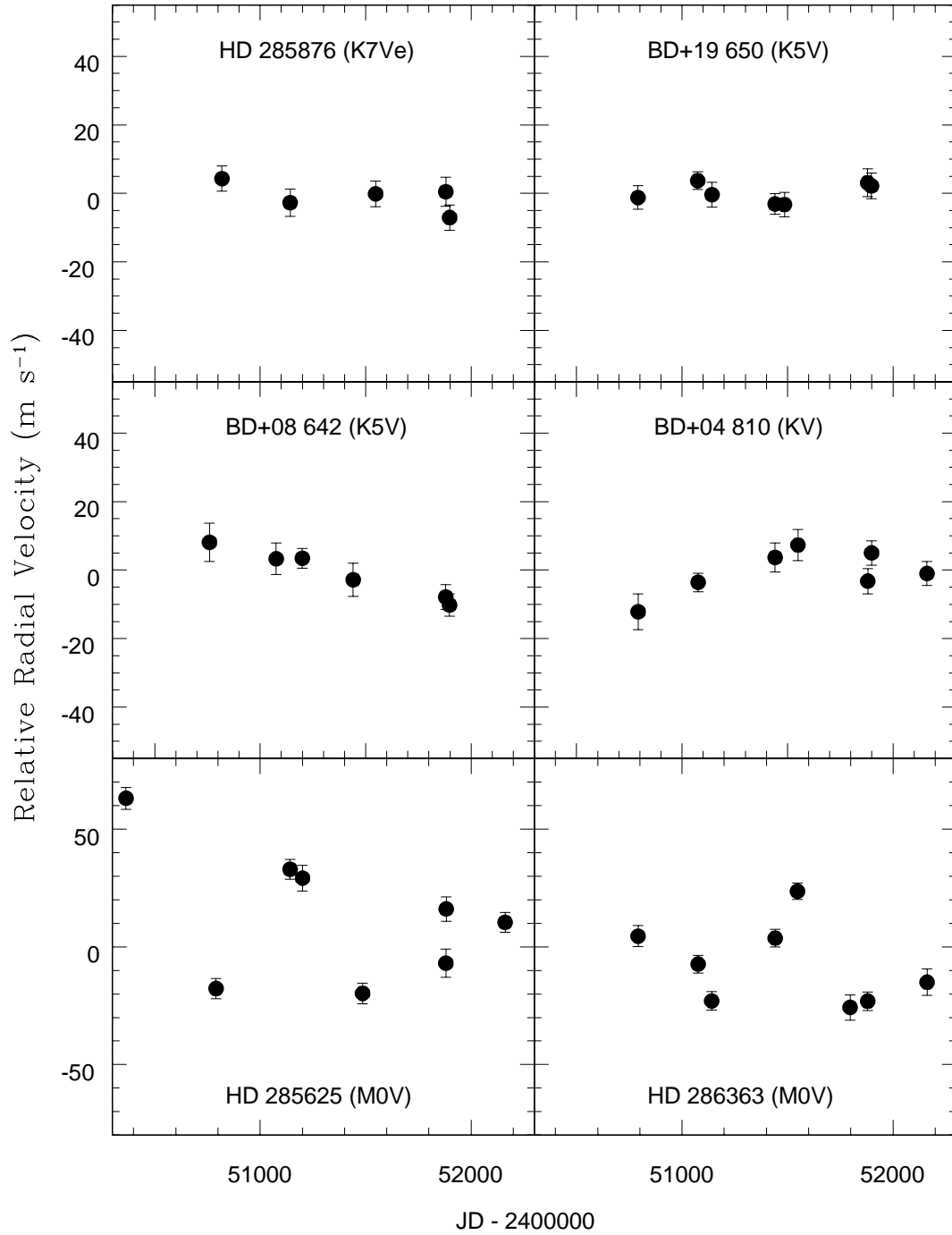
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FIG. 3.— Observed velocities for six typical stars in our Keck Hyades program. The upper two panels show two stars constant to $3\,\mathrm{m\,s^{-1}}$ over 4 years of observation. The middle panels show two stars with secular velocity trends. The lower two panels show stars with large variances which are not explained by the error bars of the individual measurements. We believe that the observed variations are intrinsic to the stellar system in some manner. These will be followed up using the Hobby·Eberly Telescope.